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Hence,

$$\begin{aligned}
 g^2 &= k^2 + [f(c - \epsilon k + k) - f(c - \epsilon k)]^2 \\
 &= k^2 + k^2 \left\{ (1 - \epsilon) \frac{f(c - \epsilon k + k) - f(c)}{-\epsilon k + k} + \epsilon \frac{f(c - \epsilon k) - f(c)}{-\epsilon k} \right\}^2 \\
 &= k^2 + k^2 [(1 - \epsilon) \tan \mu + \epsilon \tan \lambda]^2; \\
 \therefore R &= \pm \frac{k}{2} \frac{\sqrt{1 + [\epsilon \tan \lambda + (1 - \epsilon) \tan \mu]^2}}{\sin(\lambda - \mu)}, \\
 &= \pm \frac{k \sec \lambda \sec \mu}{2} \frac{\sqrt{1 + [\epsilon \tan \lambda + (1 - \epsilon) \tan \mu]^2}}{\tan \lambda - \tan \mu}.
 \end{aligned}$$

Evidently the condition for the existence of a circle of curvature is

$$\lambda - \mu = \pm 180^\circ, \text{ when } k = 0.$$

When this condition is fulfilled, the above expression for R easily reduces to the well-known expression for radius of curvature.

BERKELEY, July, 1889.

DOES THE COLOR OF A STAR INDICATE ITS AGE?

BY WILLIAM M. PIERSON.

Much discussion has been indulged in as to the relative ages of the stars, and widely divergent conclusions have resulted. ZOELLNER, in 1865, maintained that yellow and red stars are simply white stars in various stages of cooling. D'ARREST refused to adopt the theory. VOGEL, however, in 1874, classified the spectra of the stars on ZOELLNER's theory as being the "rational" basis. FATHER SECCHI leaned towards the same theory. Professor YOUNG indicates great doubts as to its correctness, and, in that connection, says: "But it is very far from certain that a red star is not just as likely to be younger than a white one, as to be older. It probably is now at a lower temperature, and possesses a more extensive envelope of gases, but it may be increasing in temperature as well as decreasing. At any rate, we have no certain knowledge about its age." (*Gen'l Astr.*, Sec. 858.) M. JANSSEN, Director of the Observatory at Meudon, France, has, however, maintained the same theory. An abstract of his valuable paper, read before the Institute of France, will be found in Volume 7 of the *Sidereal Messenger* (p. 202). His conclusions are that in-

asmuch as the bluish star indicates, spectroscopically, the existence of large quantities of hydrogen in its composition, it is probably the hottest, while stars more or less red, such as our sun and *Aldebaran*, where the spectrum displays the existence of large quantities of metallic vapors, have passed the stage of most active radiation. Thus the blue star, on that theory, would be the youngest, and the red star the oldest.

In the hope that further discussion of this interesting subject may not be wholly useless, I venture, with great hesitation, the following suggestions :

If we knew, approximately, the relative sizes of two stars, and also knew that the two stars had a common origin, and were, therefore, in all probability, composed of the same constituent elements, it would seem probable that the external appearance or color of the two might be an index of their relative ages, or their relative development from their common origin.

Do not the binary stars afford us these important conditions ?

As we shall hereafter see, in all these binary systems, where the components are of unequal magnitude, the color of the smaller of the two stars is invariably nearer the blue end of the spectrum than that of the larger.

As to the relative size of the two components, it is evident that, whether the orbit of the binary be perpendicular to our line of sight or not, we know that the two components are, substantially, equally distant from the eye. If the apparent magnitude of one be less than that of the other, we know that it is because the one is actually smaller than the other, and not because, as in instances of double stars not binary, one may be at an enormously greater distance than the other.

As to their common origin, there are three possible theories, so far as our present scientific knowledge extends :

First—That in the proper motion, which all stars have, two suns may have come within the range of each other's attraction, and into orbital relations with each other ;

Second—That two distinct nebulous masses have, in like manner, been brought into the same orbital relations, ripening afterwards into suns ; and,

Third—That the two suns are the product of one nebulous mass, one part thrown off or rather left behind by the rotation of the original mass, according to the LAPLACE theory, and both thereafter

condensing into suns, and revolving around a common center of gravity.

The first theory is inadmissible, unless we are to conclude that in the journeys of the stars through space the larger star, whose light was lowest in the spectrum, always chanced to draw within its attraction a smaller one, whose light was higher. The chances of all these larger stars having made this peculiar selection of companions are so infinitesimally small as to require no discussion.

The second theory is not improbable, but as yet no such orbital movement of nebulae has been observed, although occasionally suspected. (FLAMMARION, in *Comptes Rendus*, t. lxxxviii, p. 27.)

The third theory is not inconsistent with the generally accepted nebular hypothesis, and on it I shall base what I have to suggest on the subject.

Assuming, then, the correctness of the nebular hypothesis and that one nebulous mass had, in contracting, left behind a portion of its mass which revolved around it or about a common centre of gravity, and that both masses had condensed into suns, we have a common origin for the binary stars, and the fact that both suns are composed substantially of the same substances.

If, then, we know, on the assumptions we have made, that two stars of a given system have a common nebulous origin, and are approximately the same distance from the eye, and that, therefore, their respective magnitudes represent a difference in their actual volumes, what does observation show as to the respective colors of the two components?

I append to this paper a table of 188 undoubtedly binary stars, the details of which I have gathered from all the sources at my command, and containing every binary whose magnitudes and colors I could collect. They are arranged in the order of the difference in magnitudes of the components from those binaries whose members are equal in magnitude to those where the difference is nine and one-half entire magnitudes.

Of 130 of these systems where the companions do not differ more than one magnitude, the colors of the two are precisely similar or so nearly so as to require such peculiar nomenclature, as the characterizing of one as white, and the other pale white; one as yellow, the other yellowish; one bluish white, the other purplish white, etc. As the disparity in magnitude increases, so does the disparity in color,—the smaller of the two invariably assuming a hue nearer the blue end of the spectrum than the larger until, in the in-

stances of STRUVE, 946, β *Leporis*, ι *Ursæ Majoris* and *Sirius*, the light of the smaller is of such a peculiarly bluish tint, or else so dim, as to lead acute observers to suspect that it is not a companion sun, but has cooled down to the planetary stage. Thus, in the case of *Sirius*, OTTO STRUVE thought that the nature of the small companion must be either very different from *Sirius*, or it would, from its probable mass, shine as a first-magnitude star; while DAVIS asks, "Is it an enormously large globe endued with very small light-producing power? or perhaps shining by reflection from *Sirius*?"

The binary ι *Ursæ Majoris*, where the primary is of the 3.5 magnitude and yellow in color and the companion is of the thirteenth magnitude and purple, the light of the latter is so dim as to have led eminent astronomers to think that it may shine by reflected light, and to be therefore planetary, and BUFFHAM to remark that it is very dull for its size.

So β *Leporis*, where the primary is 3.5 magnitude and the companion of the eleventh, the larger star is yellow and the companion blue—but the latter is so dark as to also lead observers to suspect that it is planetary.

The binary STRUVE 946 is composed of a 7.5 and a tenth-magnitude star, but the smaller is again thought to have reached the planetary stage.

In other words, in all these binary systems, if the stars are of the same size, they are invariably of the same color; if, on the other hand, the magnitudes differ, the colors of the components differ in an approximately exact ratio, and where one of the members is smaller than the other, its color is invariably nearer the blue end of the spectrum than that of the larger. Thus, if the larger is red, the smaller may be yellow or white; if the larger is yellowish or white, the smaller is green, or lilac, or blue; while no binary has ever been discovered where the larger star is blue or white and its smaller companion yellow or red; or where the smaller was nearer the red end of the spectrum than its primary.

Assuming then that two stars have the same nebulous origin, are exposed to the same conditions in space, that the smaller of the two is invariably of a hue farther removed from the red end of the spectrum than the larger, the question arises—which is the older? *i. e.*, which the more developed from the original nebulous condition,—the larger or more nearly red, or the smaller or more nearly blue?

If the bluer star be the hotter, and, therefore, the newer, or

more recently emerged from its nebulous origin, then if the binary stars are to be included in the discussion, the smaller of two bodies composed of the same elements, and having a common origin, must be the hotter. Of course, this may be so, for in all of these speculations we are dealing tentatively.

But the laws of heat and of the cooling of masses would seem to be opposed to that theory. Of two masses of matter of unequal volume, but having a common origin, and of the same original temperature, the smaller mass would cool and contract more rapidly than the larger under similar conditions. In our own solar system it is manifest that the moon has cooled more rapidly than the earth, and the smaller and terrestrial planets and asteroids than the larger ones, *Jupiter* and *Saturn*.

When in the nebular evolution the mass which now represents the planet *Jupiter* was left behind by the mass now the sun, it must have been as hot as the mass from which it separated. When, afterwards, it assumed the globular form and condensed, it was, in reality, a sun. Viewed from a point in the celestial sphere, the solar system would, undoubtedly, have then appeared as a binary system, composed of, say for illustration, stars of the second and fifteenth magnitude. But the sun *Jupiter*, under the laws relating to physics, cooled more rapidly than the sun *Sol*, and, finally, after ages of cooling, assumed its present planetary form (although still, perhaps, shining to some extent by its own light).

If, then, we are to apply to these binary systems the laws of heat and of the cooling of masses; if we are to be guided by the analogies of our own solar system, and if it be not unreasonable to assume that the same laws operate in other systems, then it would seem to follow that the smaller of two components of a binary star cannot be of a higher temperature than the larger, and, therefore, must be older in development from the nebulous stage. If that be so, then observation of the binary stars proves that the cooler the star the **more** its color tends toward the blue end of the spectrum. It would further seem to be a fair deduction from that conclusion that the **tendency** towards the blue in the color of any star, binary or independent, would indicate that the star is cooler and older, relatively, than the star whose hue tends towards the red or yellow.

TABLE OF BINARY STARS, WITH RELATIVE COLORS AND MAGNITUDES.

Binaries indicated by (*) are those whose orbits have been computed.

No.	BINARY STARS.	MAGNITUDES.		Difference in Magnitudes.	COLORS.
1.	Struve, 367	8	8	0.0	Both yellowish white.
2.	Struve, 1517	7.3	7.3	0.0	Both faint yellow.
3.	42 Coma Ber.*	6	6	0.0	Both white or both yellow.
4.	γ Cor. Austral.* . . .	6	6	0.0	Both faint yellow.
5.	Struve, 2173*	6	6	0.0	Both yellow gold.
6.	Struve, 1037*	7.1	7.1	0.0	Both yellowish.
7.	ρ Eridani*	6	6	0.0	Both yellow.
8.	γ Virginis*	3	3	0.0	Both yellow.
9.	δ Equulei*	4.5	4.5	0.0	Both yellow.
10.	Struve, 186	7.2	7.2	0.0	Both white.
11.	O. Struve, 187	7.3	7.3	0.0	Both white.
12.	Struve, 1883	7	7	0.0	Both yellowish.
13.	Struve, 3091	7.7	7.7	0.0	Both yellow.
14.	Struve, 1934	8.5	8.5	0.0	Both white.
15.	Struve, 572 (4 Aurigæ)	6.5	6.5	0.0	Both yellowish.
16.	Struve, 577	7.7	7.7	0.0	Both white.
17.	Struve, 589	8	8	0.0	Whitish yellow.
18.	Struve, 619	8.7	8.7	0.0	Both white.
19.	Struve, 1093	8.2	8.2	0.0	Both white.
20.	Struve, 2267	8	8	0.0	Both white.
21.	Struve, 2799 (20 Pegasi)	6.6	6.6	0.0	Both yellowish.
22.	Struve, 2928	8	8	0.0	Both white.
23.	Otto Struve, 495	7.4	7.4	0.0	Both white.
24.	Struve, 3056	7.4	7.4	0.0	Both yellowish.
25.	Struve, 3050	6	6	0.0	Both yellowish.
26.	Struve, 1348	7.5	7.6	0.1	Both white.
27.	γ Tauri	6.6	6.7	0.1	Both white yellowish.
28.	μ Draconis*	5	5.1	0.1	White, pale white.
29.	ζ Aquarii*	4	4.1	0.1	Flushed white, creamy.
30.	Struve, 1819*	7.9	8	0.1	Both yellowish.
31.	λ Cassiopeæ	6.0	6.1	0.1	Both white.
32.	Struve, 749	7.1	7.2	0.1	Both whitish.
33.	Struve, 932	8.2	8.3	0.1	Both white.
34.	Otto Struve, 156	6.5	6.6	0.1	Both white.
35.	Struve, 2422	7.6	7.7	0.1	Both white.

36. H. 2036 (187 Ceti)	7	7.2	0.2	Both white.
37. Otto Struve, 170...	7.1	7.3	0.2	Both white.
38. 22 Cygni.....	7.4	7.6	0.2	Both yellowish.
39. ζ Cancrī.....	5.5	5.7	0.2	Both yellow.
40. 49 Serpentis.....	6.7	6.9	0.2	Pale white, yellowish white.
41. Struve, 1338.....	7	7.2	0.2	Both white.
42. Otto Struve, 298*.	7	7.3	0.3	Both yellow.
43. ξ Scorpii*.....	4.9	5.2	0.3	Both yellowish.
44. Struve, 2.....	6.3	6.6	0.3	Yellow, deeper yellow.
45. ε ² Lyræ.....	4.9	5.2	0.3	Both white.
46. Struve, 3121*.....	7.5	7.8	0.3	Both yellowish white.
47. Struve, 1126.....	7.2	7.5	0.3	White, ashy white.
48. Struve, 677.....	7.7	8	0.3	Both white.
49. Struve, 1643.....	8.4	8.7	0.3	Both white.
50. Struve, 1647.....	7.5	7.8	0.3	Both white.
51. Struve, 1785.....	7.2	7.5	0.3	Both white.
52. Struve, 1820.....	8.2	8.5	0.3	Both yellowish.
53. Struve, 1863.....	7.1	7.4	0.3	Both yellowish.
54. ε Arietis.....	5.7	6	0.3	Both white.
55. Otto Struve, 234*.	7	7.4	0.4	Both white.
56. Struve, 1781.....	7.8	8.2	0.4	Both yellowish white.
57. Otto Struve, 261..	6.3	6.7	0.4	Both white.
58. ζ Boötis.....	3.5	3.9	0.4	Both white.
59. Struve, 1074.....	7.8	8.2	0.4	Both white.
60. Struve, 2847.....	7.6	8	0.4	Both yellowish.
61. η Coronæ Bor.*..	5.2	5.7	0.5	Both yellow.
62. α Geminorum*..	3	3.5	0.5	Bright white, pale white.
63. Struve, 1876.....	8.1	8.6	0.5	Both yellowish.
64. Struve, 13.....	6.6	7.1	0.5	Both yellowish.
65. ζ Sagittarii*.....	3.5	4	0.5	Colors not found.
66. P xxii.....	6	6.5	0.5	Both white.
67. Struve, 3046.....	8	8.5	0.5	Both yellowish white.
68. Struve, 3006.....	8.5	9	0.5	Both white.
69. σ Coronæ*.....	8.6	9.1	0.5	Both white.
70. Struve, 266.....	7.5	8	0.5	Both white.
71. Struve, 1932.....	5.6	6.1	0.5	Both white.
72. Struve, 1937.....	5.2	5.7	0.5	Both yellow.
73. Struve, 257.....	7.2	7.7	0.5	Both yellowish white.
74. Otto Struve, 52...	6.2	6.7	0.5	Both white.
75. Struve, 511.....	7.5	8	0.5	Both white.
76. 20 Draconis.....	6.4	6.9	0.5	Both white.

77. Struve, 2384	8	8.5	0.5	Both yellow.
78. Struve, 2556	7.3	7.8	0.5	Both white.
79. ε Equulei	5.7	6.2	0.5	Both yellowish.
80. Struve, 2026	8.6	9.1	0.5	Both yellow.
81. Struve, 1500	7.6	8.2	0.6	Both yellowish.
82. Struve, 1944	7.5	8.1	0.6	Both white.
83. Struve, 2199	7.2	7.8	0.6	Both yellowish.
84. Struve, 2438	7	7.6	0.6	Both white.
85. Struve, 742	7.2	7.8	0.6	Yellowish, white.
86. φ Ursæ Majoris*	5	5.6	0.6	Colors not found.
87. μ Boötis*	6.7	7.3	0.6	Both greenish white.
88. 61 Cygni*	5.3	5.9	0.6	Yellow, deeper yellow.
89. τ Ophiuchi*	5	5.7	0.7	Both yellowish white.
90. Struve, 73	6.2	6.9	0.7	Both golden.
91. Struve, 1216	7.5	8.2	0.7	Both white.
92. 8 Sextantis	8.6	9.3	0.7	Both yellowish.
93. Otto Struve, 224 . .	7.3	8	0.7	Colors not found.
94. Struve, 1734	7.2	7.9	0.7	Both white.
95. Struve, 910	8.3	9	0.7	Both yellowish.
96. Struve, 1081	7.8	8.5	0.7	Both white.
97. Struve, 2744	6.3	7	0.7	Both white.
98. Struve, 2804	7.3	8	0.7	Both white.
99. Struve, 1356	6.2	7	0.8	Both yellow.
100. Struve, 1476	7.2	8	0.8	Both white.
101. Otto Struve, 215 . .	6.5	7.3	0.8	White, ashy white.
102. 14 (ι) Orionis* . .	6	6.8	0.8	Both white.
103. ω Leonis*	6.2	7	0.8	Yellow, yellower.
104. Struve, 945	7.1	8	0.9	Both white.
105. ξ Ursæ Majoris* . .	4	4.9	0.9	White, grayish white.
106. Struve, 228	6.7	7.6	0.9	Both white.
107. 12 Lyncis	5.2	6.1	0.9	Both yellowish white.
108. Struve, 1187	7.1	8	0.9	Both white.
109. Struve, 234	7.8	8.7	0.9	Both white.
110. Struve, 305	7.3	8.2	0.9	Both yellow.
111. Struve, 1457	7.4	8.4	1.0	Both yellowish white.
112. Struve, 1808	8	9	1.0	Both white.
113. 66 Piscium	6.2	7.2	1.0	Both white.
114. 42 Ceti	6.2	7.2	1.0	Both white.
115. Struve, 676	7.5	8.5	1.0	Both white.
116. Struve, 2315	7	8	1.0	Both white.
117. Struve, 2822	4	5	1.0	White, whitish blue.

118. Struve, 1989	7.1	8.1	1.0	Both white.
119. Struve, 2934	8.2	9.2	1.0	Whitish yellow, white.
120. Struve, 941	7	8	1.0	Bluish white, purplish white.
121. μ^2 Herculis*	9.5	10.5	1.0	Both white.
122. δ Serpentis	3	4	1.0	Yellow, ashy yellow.
123. α Centauri	1	2	1.0	Both yellowish or reddish.
124. 36 Andromedæ*	6.	7	1.0	Bright orange, yellow.
125. Otto Struve, 400*	7.2	8.2	1.0	Colors not found.
126. Struve, 3062*	6.9	8	1.1	Yellowish white, bluish.
127. Struve, 1757*	7.8	8.9	1.1	Pale white, yellowish.
128. Struve, 2509	7	8.1	1.1	Both yellowish.
129. Struve, 2289	6	7.1	1.1	Both bluish.
130. Struve, 2114	6.2	7.4	1.2	Both white.
131. Struve, 963	5.9	7.1	1.2	Golden, purplish.
132. Struve, 1639	6.7	7.9	1.2	White, ashy.
133. Otto Struve, 338	6.5	7.7	1.2	Both yellow.
134. Struve, 1374	7	8.3	1.3	Yellowish, sky blue.
135. 37 Pegasi	5.8	7.2	1.4	Both white.
136. Otto Struve	6.3	7.7	1.4	White, ashy olive.
137. γ Leonis*	2	3.5	1.5	White, gray green.
138. Struve, 2107*	6.5	8	1.5	Yellowish, bluish.
139. 32 Orionis	5.2	6.7	1.5	Both yellowish.
140. Struve, 2281	5.7	7.2	1.5	Both white.
141. Struve, 535	6.7	8.2	1.5	Yellowish, bluish.
142. Struve, 1104	6.7	8.3	1.6	Both white.
143. Otto Struve, 296	7	8.6	1.6	Colors not found.
144. ϕ Andromedæ	4.9	6.5	1.6	Yellow, green.
145. Struve, 1837	7.1	8.7	1.6	Pale yellow, greenish.
146. Struve, 2106	6.7	8.4	1.7	Both white.
147. ξ Boötis*	4.7	6.6	1.9	Deep yellow, flushed purple.
148. γ Andromedæ	3.5	5.5	2.0	Deep yellow, sea green.
149. Struve, 208	6.5	8.5	2.0	Yellow, pale gray.
150. 4 Aquarii*	4.5	6.5	2.0	Pale yellow, purple.
151. ξ Cephei	5	7	2.0	Yellowish, bluish.
152. 40 (α^2) Eridani*	9	11	2.0	Orange, sky blue.
153. 70 Ophiuchi*	4.1	6.1	2.0	Topaz, purplish.
154. Otto Struve, 483	6	8	2.0	White, ashy.
155. Otto Struve, 413	5.5	7.6	2.1	White, ashy.
156. λ Ophiuchi	4	6.1	2.1	Yellowish, bluish.
157. Struve, 422	6	8.2	2.2	Yellow, blue.
158. ϵ' Lyrae	4	6.3	2.3	Yellowish, bluish.

159. 2 Camelopardali.	5.1	7.4	2.3	Yellow, bluish.
160. π Cephei*	5.2	7.5	2.3	Yellow, purple.
161. τ Cygni	5.6	7.9	2.3	Yellow, blue.
162. β Cygni	3	5.3	2.3	Gold yellow, smalt blue.
163. 38 Geminorum	5.4	7.7	2.3	Light yellow, purple.
164. α Virginis	5.8	8.2	2.4	Yellowish, smalt blue.
165. Struve, 946	7.5	10	2.5	White, blue Companion suspected to be planetary.
166. Otto Struve, 159	4.7	7.2	2.5	Yellow, bluish.
167. α Cephei	5.2	7.8	2.6	Yellow, very blue.
168. 25 Can. Venat.*	5	7.6	2.6	White, blue.
169. 35 Comæ Bor.	5	7.8	2.8	Yellowish, blue.
170. ι Cassiopeiæ	4.2	7.1	2.9	Yellow, blue.
171. γ Cor. Boreal.*	4	7	3.0	Greenish white, purple.
172. Struve, 489	4.4	7.5	3.1	Yellow, Olive green.
173. ι Leonis	4.8	7.9	3.1	Yellowish, blue.
174. α^2 Ursæ Majoris	5	8.2	3.2	Flushed white, sapphire blue.
175. Struve, 295	6	9.2	3.2	Yellow, ashy.
176. ϵ Boötis	3	6.3	3.3	Reddish, bluish.
177. η Cassiopeiæ*	4	7.6	3.6	Yellowish white, purple.
178. ϵ Draconis	4	7.6	3.6	Light yellow, blue.
179. γ Ceti	3	6.8	3.8	Pale yellow, lucid blue.
180. 84 Ceti	6	10	4.0	Yellow, blue.
181. ϵ Hydræ	3.8	7.8	4.0	Pale yellow, purple.
182. δ Cygni*	3	7.9	4.9	Pale yellow, greenish blue.
183. Struve, 1066	3.2	8.2	5.0	Yellowish, purplish.
184. α Scorpii (Antares)	1	7	6.0	Red, green.
185. β Leporis	3.5	11	7.5	Deep yellow; companion blue. Companion suspected to be a planet.
186. β Delphini*	4	12 & 15	8.0	Triple; primary greenish, companions dusky.
187. α Canis Majoris } (Sirius)*	1	10	9.0	Primary white; companion dim. Companion suspected to be a planet.
188. ι Ursæ Majoris	3.5	13	9.5	Primary deep yellow; companion blue. Companion suspected to be a planet.

NOTE.—The foregoing table is compiled from the list of binary stars appended to Professor HOLDEN's paper on the colors of binaries in the *American Journal of Science*, vol. XIX, p. 467; the list in Mr. GORE's appendix to Professor BURNHAM's article on Double Stars in "Astronomy for Amateurs"; Professor YOUNG's table in his "General Astronomy"; and from WEBB's "Celestial Objects."